STUDIES IN K-CAPTURE POSITRON BRANCHING RATIOS-CO^{58}*

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(*Received March* 18, 1960)

ABSTRACT. One of the methods of determining the Fierz term in Gamow-Teller-transitions is by means of precise determinations of K/β^+ ratio. With this in mind the amount of positron emission in the decay of Co 58 has been measured using coincidence scintillation methods. The measured value is 0.151 ± 0.005. This leads to a K/β^+ ratio of 5.08 ± 0.17 to the 0.810 MeV level in Fe^{58}. On the assumption that the beta transition is pure Gamow-Teller, the Fierz term is computed to be -0.004 ± 0.014.

GENERAL INTRODUCTION

a. *The interaction in beta decay*

The central problem in the theory of beta-decay has been the determination of the nature of the interaction responsible for this decay. In general the interaction can be a linear combination of five types, namely, scalar (S), vector, (V), tensor (T), axial vector (A) and pseudoscalar (P), all satisfying the requirement of relativistic invariance. Beta-Decay can be classified as allowed or forbidden depending on the change in angular momenta and parities of the nuclear states involved. The selection rules permit a further distinction between transitions as Fermi or Gamow-Teller. The selection rules are :

Allowed	$\Delta J = 0$	Fermi
	No	
	$\Delta J = 0, \pm 1$	Gamow-Teller
	No 0—0	
First forbidden	$\Delta J = 0, \pm 1, \pm 2$	Gamow-Teller
	Yes	
	$0, \pm 1$	Fermi

and so on.

The Fermi transitions involve only the interactions S and V, and the interactions A and T characterize Gamow-Teller transitions. A transition allowed

*Supported in part by the U.S. Atomic Energy Commission

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Present Address : Dept. of Physics, The Ohio State University, Columbus, Ohio (USA) by both types of selection rules should therefore involve S, V, A, T and perhaps P. There is strong evidence that the P interaction is unimportant. The fact that transitions obeying both kinds of selection rules are observed indicates that the beta-interaction is an admixture of both Fermi and Gamow-Teller types. It remains to determine the ratio of these interaction strengths. A study of the angular correlation between the electron and the neutrino in an allowed pure transition can be used to distinguish which of the interactions S or V, or A or T is predominant. It is now established from such experiments [Hermansfeldt. (1957, 1958), Alford (1954), Burman (1959)] that the Fermi interaction is mostly V and the Gamow-Teller interaction mostly A. The neutron decay (mixed transition) combined with the O^{14} decay (pure Fermi transition) leads to the determination of the relative strengths of Fermi and Gamow-Teller interactions. The recent Russian measurement (Sosnovski, 1959) of 11.7 ± 0.4, min. for the half life of neutron leads to $(C_{GT}/C_F)^2 = 1.42 \pm 0.08$.

Considering only pure transitions, Fermi or Gamow-Teller one can expect interference between the two types S and V, or A and T. The possible existence of such terms was first pointed out by Fierz (1937) and hence these terms are called Fierz interference terms. It is the principal objective of the present work to make an estimate of this effect in Gamow-Teller transitions. Such interference is possible in the electron-neutrino angular correlation expression, but because of the difficulties involved in such experiments these terms are often neglected. Interference between A and V in a mixed transition can also occur, but we will not concern ourselves with this here, nor will we treat forbidden transitions.

b. *Fierz interference*

The general expression for the energy distribution of electrons (positrons) in an allowed transition can be written as (Gerhart, 1958)

$$N(W)\,dW = [2\pi^3]^{-1} pW(W_0 - W)^2 F(Z, W)\zeta(1 \pm 2b/W)dW$$

where $$\xi = 1\int 1|^2 [k^{2}(|C_s|^2 + |C_s'|^2) + (|C_V|^2 + |C_V'|^2)] + 1\int\sigma|^2(|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2)$$

and $$\zeta b = \pm\gamma[\,|\int 1|^2 Re\{k^{-1}(C_S C_V^* + C_S' C_V'^*)\} + 1\int\sigma|^2 Re\{(C_A C_T^* + C_A' C_T'^*)\}]$$

Here the + sign refers to electron, and — to positron emission. The other symbols are explained as follows.

$pW(W_0 - W)^2$ is the statistical weight factor which determines, in the absence of the coulomb field, the sharing of energy between the electron and the neutrino.

$F(Z, W)$ is the coulomb field factor which represents the effect of nuclear charge on the emitted electron

p is the momentum of the electron

W is the energy of the electron in relativistic units

W_0 is the maximum energy of the electron or positron

$k = \int 1 / \int \beta$

where $\int 1$ = the scalar matrix element

$\int \beta$ = the vector matrix element

$k = 1$ only if the motion of the nucleons is non-relativistic, since in this case $\beta = \gamma_4 = 1$.

Putting $k = 1$ we get

$$b = \gamma \left[\frac{R_e(C_S C_V^* + C_S' C_V'^*) |\int 1|^2 + R_e(C_A C_T^* + C_A' C_T'^*) |\int \sigma|^2}{(|C_S|^2 + |C_S'|^2 + |C_V|^2 + |C_V'|^2) |\int 1|^2 + (|C_A|^2 + |C_T|^2 + |C_A'|^2 + |C_T'|^2) |\int \sigma|^2} \right]$$

is called the Fierz interference term. Here $\gamma = \sqrt{1-(\alpha Z)^2} \simeq 1$ represents the screening effect due to the atomic electrons.

$C_i = S, V, A, T =$ is the coupling constant for parity conserving interaction

$C_i' = S, V, A, T =$ is the coupling constant for parity non-conserving interaction.

The complex conjugation on the coupling constants represents the possibility of time reversal non-invariance in the beta-decay process.

An immediate consequence of $b \neq 0$ is that the spectral shape of an allowed transition will deviate from the statistical shape because of the inverse dependence on W through b. One way of seeing this deviation experimentally is to plot the form factor

$N(W)/F(Z, W)\, pW(W_0 - W)^2$ as a function of W. From this kind of analysis the limits set on b_{GT} are $-0.09 \leqslant b_{GT} \leqslant 0.20$. Because of the weak dependence on W such deviations are rather hard to detect. Further the analysis has so far been generally restricted to Gamow-Teller transitions only. Recently, Daniel (1958) has applied this method to estimate the Fierz term in the decay of N^{13} $(1/2^- - 1/2^-)$. He obtained $b_F = 0.14$ using the O^{14} ft value to evaluate the Fermi part of the matrix element.

Integrating expression (1) over the allowed spectrum, we obtain

$$2\pi^3 (ft^{-1}) \ln 2 = \xi + \xi b \langle W^{-1} \rangle \tag{2}$$

where $f = \int_1^{W_0} F(Z, W) pW(W_0 - W)^2 dW$ is the so-called Fermi function and

$f^{-1} \int_1^{W_0} F(Z, W) p(W_0 - W)^2 dW = \langle W^{-1} \rangle$ is the expectation value of W^{-1} over the allowed spectrum.

Thus a consequence of $b \neq 0$ is that the ft values will depend on W^{-1}. From a plot of $2\pi^3 [ft|1|^2]^{-1} \ln 2$ *vs* $2\gamma' \int 1|^2 < W^{-1} >$ which should give a straight line provided $k = 1$ and the matrix elements remain the same Gerhart (1958) finds from an analysis of data for 0 0, No (Fermi) transitions $-O^{14}$, Al^{26} and Cl^{34}, that

$$b_F = \gamma \frac{Re(C_S C_V^* + C_S' C_V'^*)}{|C_S|^2 + |C_S'|^2 + |C_V|^2 + |C_V'|^2} = 0.00 \pm 0.12$$

the chief uncertainty being due to the assumption regarding k. (Recently Altman and MacDonald (1958) have considered the effect of coulomb and relativistic corrections to the evaluation of the Fierz term and conclude that the corrections are within experimental uncertainties.) The matrix elements were evaluated by Gerhart on the basis of charge independence of nuclear forces.

Another fruitful approach for the evaluation of b has been the method of K-capture to positron branching ratios first exploited by Sherr and Miller (1954). In the following section we will describe the information that can be derived from a study of K/β^+ ratios and in particular about the Fierz term.

c. *K-Capture positron branching ratios*

The study of the shapes of beta-spectra together with the ft values and the shell model (to determine parities) has been very useful in classifying transitions as to the order of forbiddenness. When, however, between two nuclear states enough energy is available both for K-capture and positron emission, a useful quantity that can be measured is the K-capture positron branching ratio. In fact, it was one of the early triumphs of the Fermi theory of beta-decay that the K-capture mode of decay was observed as predicted. A measurement of the K/β^+ ratio can be used to find the energy difference between two nuclear states if it is known otherwise that the transition is allowed. However, it is observed (Zweifel, 1957) that all allowed shaped transitions (most first-forbidden transitions) have allowed branching ratios also. Thus it is not possible to determine whether an allowed shape transition is indeed allowed, without a knowledge of the parity change. However, the K/β^+ ratio does show a detectable change for unique first forbidden and higher transitions intensified with increasing order of forbiddenness (Brysk, 1958). These latter transitions can probably be much more easily identified on the basis of the shape of the positron spectrum and life-time. In such cases K/β^+ ratios can only serve as an additional check on the assignment. However, the chief virtue of measurement of K/β^+ ratio for supposedly pure transitionsis that it lends itself to the estimation of small-order effects in beta-decay such as the Fierz term. Consider a pure transition, say, a Gamow-Teller transition. Then for this transition the probability for positron emission is

$$P_+ = \frac{1}{2\pi^3} \int^{W_0} F(Z, W) p W (W_0 - W)^2 \xi (1 - 2b/W) dW$$

where the varius quantities have already been defined. (Note that the terms involving C_S and C_V are set equal to zero.)

The probability for K-capture to the same state can be written as

$$P_K = \frac{1}{4\pi^2}(W_0 + W_k)^2 g_k^2(R)\,\xi(1+2b)$$

where $g_k^2(R) = \frac{1+\gamma}{2\Gamma(2\gamma+1)} R^{2\gamma-2}(2\alpha Z_{eff})^{2\gamma+1}$ is the Dirac radial function,

W_0 = total energy available for the transition in m_0c^2 units,

$W_K = \gamma \simeq \sqrt{1-\alpha^2Z^2}$

So that the ratio of K-capture to positron emission becomes

$$P_K/P_+ = \frac{(1/4\pi^2)(W_0 + W_k)^2 g_k^2(R)\xi(1+2b)}{(1/2\pi^3)\int^{W_0} F(Z, W)pW(W_0 - W)^2 dW\xi(1-2b/W)} = R \qquad .. \quad (1)$$

If the Fierz interference term were zero, then putting $b = 0$, we get

$$(P_K/P_+)_{b=0} = \frac{(1/4\pi^2)(W_0 + W_k)^2 g^2_k(R)}{1/2\pi^3 \int_1^{W_0} F(Z, W)pW(W_0 - W)^2 dW} = R_0 \qquad .. \quad (2)$$

Dividing Eq. (2) by (1), we obtain

$$R/R_0 = \frac{1+2b}{[1-2b<W^{-1}>]}$$ where $<W^{-1}>$ has already been defined.

$$b = \frac{R/R_0 - 1}{2[1+R/R_0<W^{-1}>]}$$

Thus a measurement of R can be used to evaluate b. It should be noted that the matrix elements cancel out in the ratio.

Before comparing the theoretical K/β^+ ratio with the observed value, correction for the finite size of the nucleus and screening of the positron and the bound K-electron have to be made. Further, if the measured quantity is the total electron-capture, then correction for capture from higher shells has to be made to obtain the K-capture alone.

For allowed transitions the finite size correction has been shown to be negligible (Zweifel, 1957). The screening correction, on the other hand, is not insignificant. Recently Perlman, Welker and Wolfsberg (1958) have evaluated the effect of screening on the positron wave function and have given in graphical form the ratio of screened to unscreened values. For most Z values of interest the screening on the K-electron is taken into account by putting $Z_{effective} = Z_k - 0.3$. Zweifel (1957) has evaluated the deviation of the actual Z_{eff} from this Slater screening. Regarding correction for capture from higher shells, only L-capture is important for most cases of interest. (At high Z, M-capture also becomes important.) Correction for L-capture is obtained by using L/K ratios given in graphical form by Rose and Jackson (1949).

We have applied the K/β^+ ratio technique for the decays of Ga^{68}, Co^{58} and Na^{22}, all pure Gamow-Teller emitters, to obtain the Fierz interference term. The results on Ga^{68} have been reported (Ramaswamy, 1959a) briefly at the Cambridge meeting of the American Physical Society, and published elsewhere (Ramaswamy, 1959b).

INTRODUCTION

72 day Co-58 decays by electron capture and positron emission to the 0.810 MeV level in Fe-58 followed by a gamma-ray of this energy to the ground state. Besides, there is a weak electron-capture branch (2%) to the second excited state at 1.63MeV. This level de-excites itself predominantly by the emission of a gamma ray of 0.820 MeV to the 0.810 MeV level and partly by the emission of a gamma ray of 1.63 MeV to the ground state of Fe-58. The decay scheme as given by Frauenfelder *et al.* (1956) is reproduced in Fig. 4. The end-point of the positron spectrum is measured to be 0.472 ± 0.006 MeV (King, 1954). No positron emission to the 0^+ ground state of Fe-58 has been observed. The spin of 0.810 MeV level is 2^+ from systematics of even-even nuclei (Scharff-Goldhaber, 1953). The spin of the second excited state at 1.63 Mev has been assigned 2^+ from angular correlation studies. This is consistent with the presence of a cross-over gamma transition to the 0^+ ground state. The decay of Co-58 to the 2^+ states in Fe-58 and the absence of transition to the 0^+ ground state suggest a spin of 2^+ or 3^+ for Co-58. The spin has been directly measured to be 2 by Dobrov and Jeffries (1957) by means of paramagnetic resonance experiments. The assignment of 2^+ to Co-58 makes the beta transition to the 0.810 MeV level allowd by both Gamow-Teller and Fermi selection rules ($\Delta J = 0$, No). However, recent nuclear orientation experiments of Dagley *et al.* (1958) have shown that the anguar distribution of the 0.810 Mev gamma ray is consistent only with the beta transition being pure Gamow-Teller, the amount of Fermi admixture being 0.005 ± 0.003. Thus the measurement of electron capture to positron branching ratio to the 0.810 MeV level becomes of obvious interest from the point of view of determining the Fierz term.

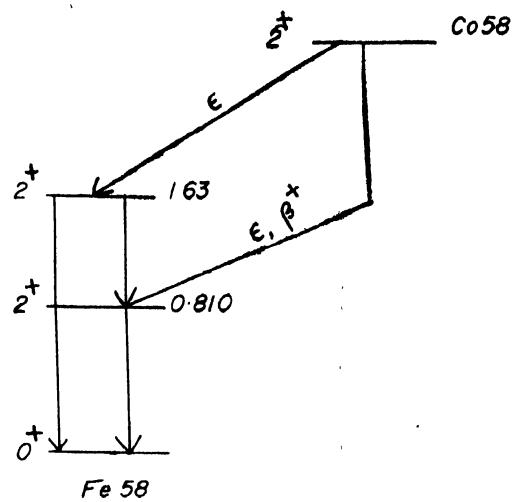
Good *et al.* (1946) and Cook and Tomnovec (1956) have measured the ratio of total electron capture to positron emission in the decay of Co-58 to be 5.9 ± 02.

When account is taken of the weak electron capture branching to the 1.63 MeV level, the K/β^+ ratio to the 0.810 MeV level becomes 5.8 ± 0.2. This result was obtained by comparison of the intensities of the annihilation radiation and the 0.81 MeV gamma ray, and by a knowledge of the efficiencies. After the work to be described on Co-58 had been completed and briefly published by the author (Ramaswamy, 1958), the work of Konijn et *al.* (1958) on the same subject has come to attention. By using beta-gamma coincidence technique these workers determined the ϵ/β^+ ratio to be 5.67 ± 0.14.

Neglecting the weak electron-capture branch ($\sim 2\%$) to the 1.63 MeV level for the moment, the fraction of positrons in the decay of Co-58 can be expressed as $f_+ = \beta/2c\sigma$, where c is the singles counting rate for the 0.810 gamma ray, β is the concidence rate between the 0.810 MeV gamma ray and the annihilation radiation, and σ is the efficiency for detecting the annihilation radiation. The value of f_+ when corrected for the presence of the weak branch will give the desired ϵ/β^+ ratio to the 0.810 MeV level.

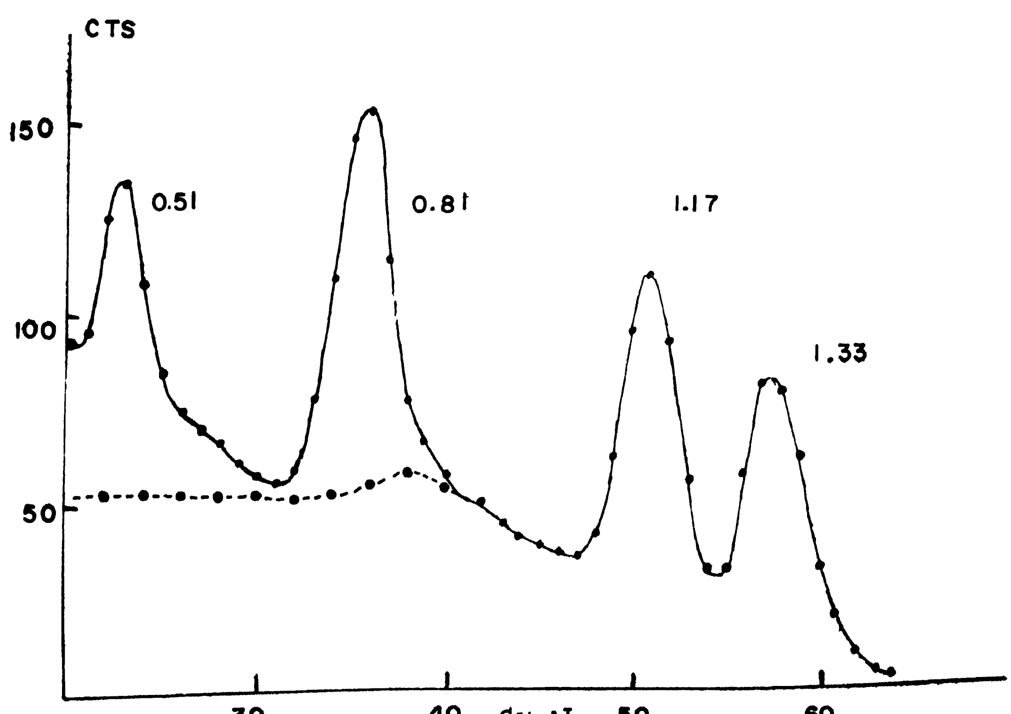
EXPERIMENTAL

Through the courtesy of Dr. R. W. Hayward of the National Bureau of Standards, Co-58 source was made available for studies. Unfortunately this source contained an appreciable Co-60 impurity. Co-58 was evaporated onto a 0.0003″ mylar foil and sealed with cellophane. The sandwich was then squeezed between two lucite slabs each 1.3 mm thick and 1 cm square. The whole assembly was then sealed with black tape. Thus the positrons from Co-58 (0.470MeV) were completely stopped. The 0.810 MeV gamma ray was detected in a 2″ cube NaI(TI) crystal and the annihilation radiation was detected in a $1\frac{1}{2}'' \times 1''$ NaI(TI) crystal. Source to detector distance of 1″ to $1\frac{1}{2}''$ was used. A typical singles gamma spectrum measured in the 2″ cube crystal is shown in Fig. 2. Besides the annihilation radiation and the 0.810 MeV gamma ray belonging to Co-58, gamma rays at 1.17 and 1.33 MeV are also prominently seen. The 1.63 MeV gamma ray of Co-58 is too weak to be seen, and no effort was made to observe it. In order to determine the number of counts in the 0.810 MeV photopeak, it is necessary to subtract the Compton background due to Co-60 gamma rays. In order to do this a pure Co-60 source was substituted and its spectrum was carefully normalized to that of Co-58, 60. The dotted curve in Fig. 2 shows the normalized spectrum. For the coincidence measurements a single channel analyzer was set on the photopeak of the annihilation radiation and the spectrum in coincidence was obtained by gating the 20-channel analyzer with the annihition radiation. The coincidence spectrum thus obtained is shown in Fig. 3. It is observed that the coincident 0.810 MeV gamma ray is superposed on a rather high background due to Co-60. In order to estimate and subtract this background, a coincidence spectrum was taken by replacing Co-58 by Co-60 and the spectrum normalized to the Co-58 spectrum. The resulting background was thus subtracted.



2+
Co58
ε
2+
1.63
ε, β+
2+
0.810
0+
Fe 58

Fig. 1,



CTS
150
100
50
0.51
0.81
1.17
1.33
30
40
50
60
CH No

Fig. 2.

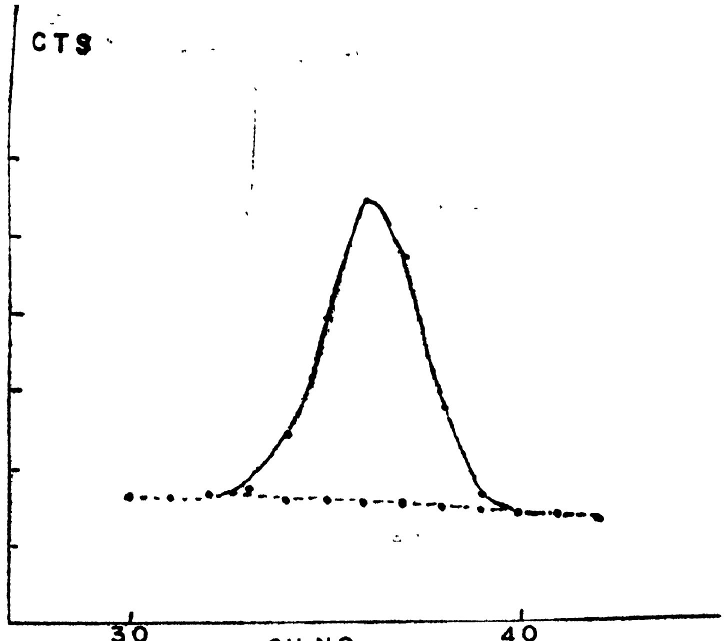


Fig. 3.

In order to check on the reliability of this procedure, the 0.810 MeV gamma ray was measured in triple coincidence with the two annihilation quanta. From this it was concluded that the background had been correctly estimated. The accidentals were about 10 per cent of true coincidences in the doubles spectrum.

In order to determine σ, the efficiency for detecting annihilation radiation initially a calibrated Na^{22} source (accurate to 3%) was used. By measuring the area under the photopeak and knowing the source strength one could compute the efficiency. A more accurate efficiency determination was made as follows: A N^{13} source (a pure positron emitter of 10 minutes half life) was produced by bombarding a 2 mil polyethelene foil for 10 minutes with 1 MeV deuterons at the Johns Hopkins University Van de Graaff generator through the courtesy of O.N. Rask. After the bombardment the foil was cut into a tiny piece approximating the dimensions of the Co-58 source and sandwiched between two freshly cleaved NaI(TI) crystals 1.2 mm thick and 1 cm square, and mounted in the same geometry as the Co-58 source. The beta spectrum observed in this system is shown in Fig. 4. The energy calibration of the counter was made after the N^{13} source was dead by using external gamma ray sources of Co^{57} (0.123 MeV), Cs^{137} (0.661 MeV) and Na^{22} (1.28 MeV). A Fermi plot of the spectrum is shown in Fig. 5. It has an end-point of 1.16 ± 0.05 MeV, in good agreement with the value of 1.20 MeV (Scharff-Goldhapper, 1953). By following the decay of the activity for 3 half- lives, it was concluded that no impurities were present. Under the conditions of the bombardment, no other impurities were likely to be formed.

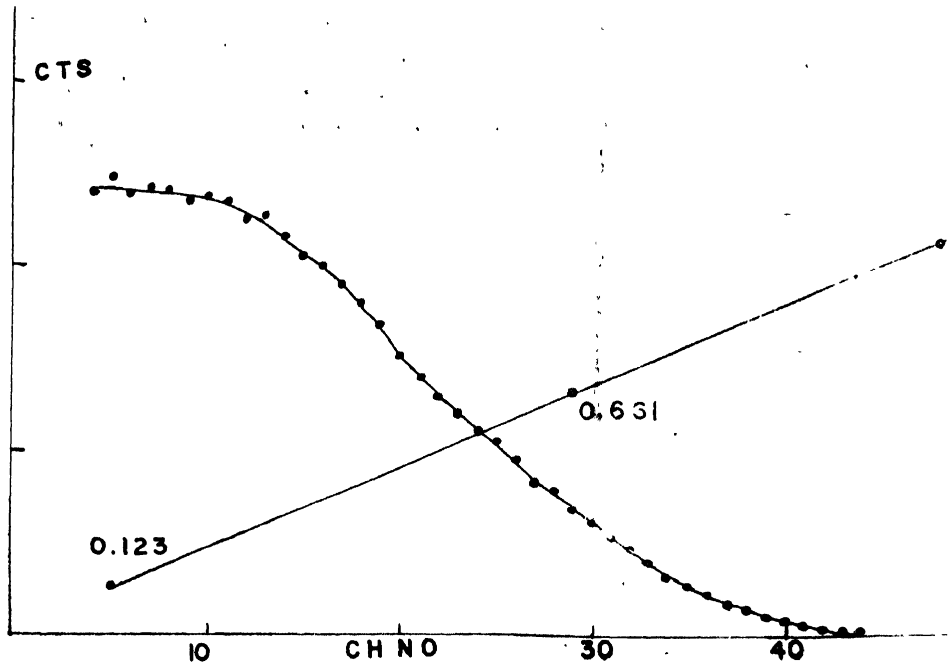

CTS
0.631
0.123
10
CH NO
30
40

Fig. 4.

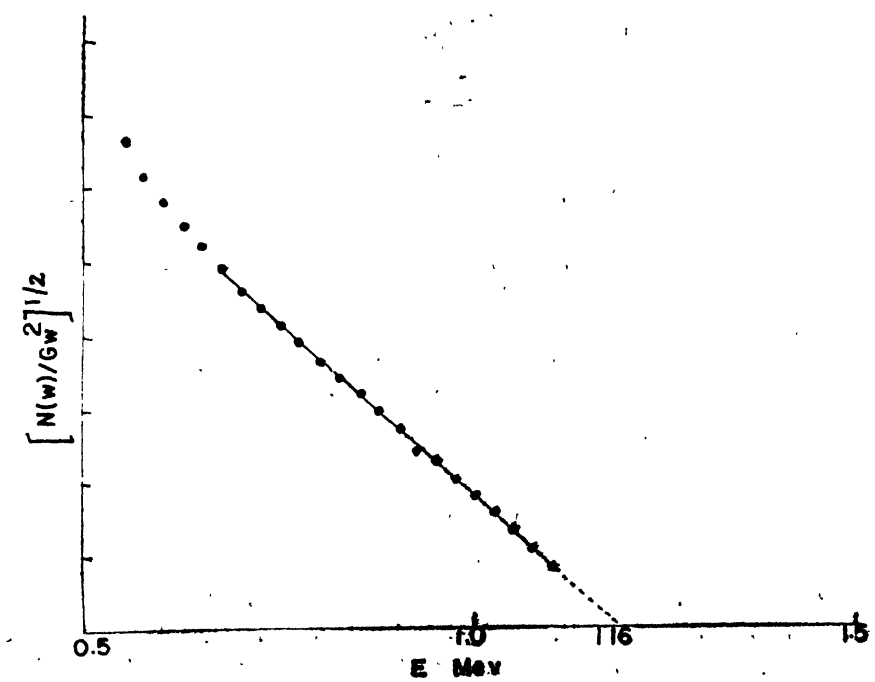

$\left[N(w)/Gw^2\right]^{1/2}$
0.5
1.0
1.16
1.5
E Mev

Fig. 5.

The beta-spectrum was measured in coincidence with the annihilation radiation photopeak which was detected by the same $1\frac{1}{2}'' \times 1''$NaI counter whose efficiency was to be determined. A portion of the beta spectrum is shown in Fig. 6. The efficiency for detecting the annihilation radiation is simply the ratio of the beta-spectrum in coincidence and in singles when corrected for decay.

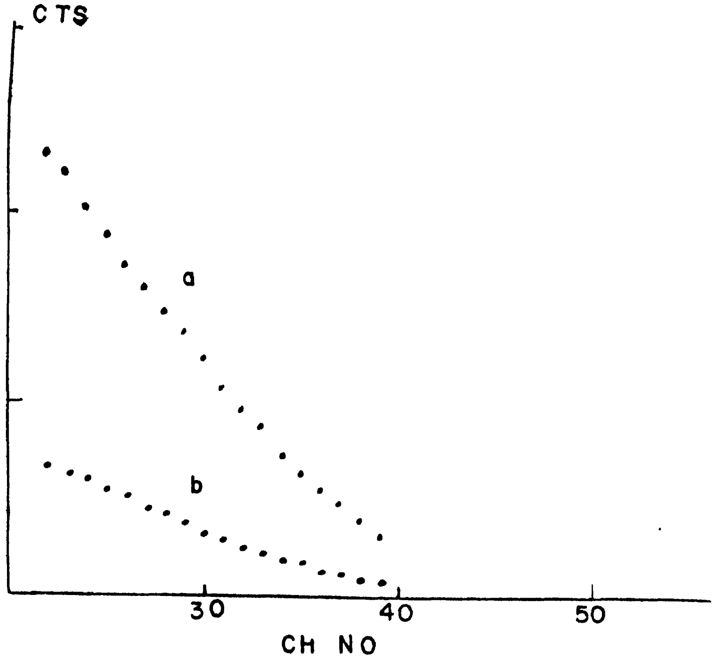


Fig. 6.

Further, since the crystal source was mounted on a light pipe, a correction for the absorption of the 0.511 MeV gamma ray has to be made. This is of the order of 3.7 %. Since the positrons from Co^{58}(0.470MeV) and those from N^{13} (1.2 MeV) have different ranges in lucite and NaI respectively used to annihilate them. one might think that a correction for solid angle has to be made. However, the range of 0.470 MeV positrons of Co^{58} in lucite is 1.4 mm and that of 1.2 MeV positrons of N^{13} in NaI (Tl) is 1.16 mm. The actual thickness used to annihilate the positrons were 1.3 and 1.2 mm respectively. A source to detector distance of 25 mm was used. In view of these circumstances the solid angle correction is less than 1%.

RESULTS

Table 1 lists the results obtained. The uncorrected f_+ is 0.147 ± 0.005. Refering to the Co-58 decay scheme (Fig. 1), it is seen that $1\frac{1}{2}\%$ of the 0.810 MeV gamma rays arise from the 1.63 MeV level, and another $1\frac{1}{2}\%$ arise from cascading to the ground state. The uncorrected f_+ has therefore to be multiplied by 0.03 to get the corrected value of f_+. In order to obtain the amount of electron-capture to the 0.810 MeV level, it should be noticed that 2% of the Co-58 transitions lead to the 1.63 MeV level. Hence $\epsilon = 0.98 - 0.151 \pm 0.005$. Thus the ϵ/β^+ ratio to the 0.810 MeV level is computed to be 5.49 ± 0.18. The error introduced in the value of 2% for the branching is very small.

DISCUSSION

The ϵ/β^+ ratio computed above has to be corrected for 8% L-capture to give (Gerhart, 1958) the value K/β^+ ratio. The value so obtained is 5.08 ± 0.17. The theoretical value is 5.15 ± 0.24 corresponding to maximum beta energy of 0.472 ± 0.006MeV. Thus our value is in excellent agreement both with theory and with previous measurements. As before, the Fierz term is computed from the expression

$$b = \frac{R/R_0 - 1}{2[1 + R/R_0 < W^{-1} >]}$$

For Co-58 $< W^{-1} > \quad = 0.76$ corresponding to $W_0 = 1.924$.

$$b = -0.004 \pm 0.014$$

TABLE I

Summary of results on Co^{58}

(For symbols see text)

$c = 91.00 \pm 1.12$ cps

$\beta = 0.242 \pm 0.003$

σ : (a) from Na^{22}

Source strength $= N_0 =$ no. of positrons/min $= (3.16 \pm 0.10) \times 10^5 \beta^+$/min

a = no. of cts in the 0.511 photopeak $= 47.0 \pm 0.0$ cps

$\sigma = a/N_0 = (8.92 \pm 0.33) \times 10^{-3}$

(b) from N^{13}

$N\beta, 0.5 = 358.0 \pm 6.0$ cpm

$N\beta = 23200 \pm 150$ cpm

$$\sigma = \frac{1}{2} \frac{N\beta 0.5}{N\beta} = (9.02 \pm 0.18) \times 10^{-3}$$

f_+ (uncorrected) $= \beta/2c\sigma = 0.147 \pm 0.005$

f_+ (corrected) $= (0.147 \pm 0.005)\ 1.03 = 0.151 \pm 0.005$

$\epsilon = 0.980 - f_+ = 0.829 \pm 0.005$

$$\epsilon/\beta^+ = \frac{0.829 \pm 0.005}{0.151 \pm 0.005} = 5.49 \pm 0.18$$

$L/K = 0.08$

$K/\beta^+ = 5.08 \pm 0.17$

CONCLUSIONS

The fraction of Co-58 decays by positron emission has been measured by coincidence methods using NaI crystals. The value is 0.151 ± 0.005. This value leads to a K/β^+ ratio of 5.08 ± 0.17 for the beta transition to the 0.810 MeV level

The theoretical ratio is 5.15 ± 0.24. The Fierz term is computed to be -0.004 ± 0.014. It is rather striking that the theoretical value of K/β^+ ratio has a larger error than the measured value.

It follows then that the Fierz interference term is extremely small. Unfortunately Co-58 is not the best case, since a small admixture to Fermi component in the beta transition may invalidate the conclusions reached so far. However, if it turns out, as is likely, that the Fermi component is zero, then it may be worth while to measure the end-point of the positron spectrum more accurately. The smallness of the Fierz term has been conclusively shown from Na^{22} decay (*R*amaswamy, 1959c)

ACKNOWLEDGMENTS

The author wishes to express his deep appreciation to Prof. L. Madansky for valuable suggestions and discussions.

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